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14. ABSTRACT

Over the past several years we have been conducting VLF wave injection experiments at Arecibo Observatory, Puerto Rico, guided by our theoretical and numerical analyses, to investigate whistler wave interactions with inner radiation belts as well as the ionospheric effects caused by precipitated energetic electrons. The whistler waves used in our experiments were launched from the 100 kW and 40.75 kHz transmitter code-named NAU, which is operated by the United States Navy at Aguada, Puerto Rico, about 52 km to the west of the Arecibo Observatory. This report focuses on experiments in which the Arecibo Incoherent Scatter Radar (ISR) and ionosonde monitored properties of local ionosphere on the night of January 1-2, 2006. We examine possible correlations between occurrences of nighttime E-region plasma line (PL) enhancements over Arecibo and 40.75 kHz NAU emissions. We find that the NAU radiations can propagate in whistler mode into the $L = 1.35$ inner radiation belts where gyroresonant interactions with trapped 390 keV electrons increase the precipitation and radar detection rates of enhanced plasma lines.

15. SUBJECT TERMS

Inner radiation belts; whistler waves; VLF wave injection experiments; whistler wave interactions with radiation belts; gyroresonant interactions between whistler waves and trapped energetic electrons; electron precipitation; plasma line enhancements.

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Controlled Studies of Whistler Wave Interactions with Energetic Particles in Radiation Belts

Abstract

Over the past several years we have been conducting VLF wave injection experiments at Arecibo Observatory, Puerto Rico, guided by our theoretical and numerical analyses, to investigate whistler wave interactions with inner radiation belts as well as the ionospheric effects caused by the precipitated energetic electrons. The whistler waves used in our experiments were launched from the 100 kW and 40.75 kHz transmitter code-named NAU, which is operated by the United States Navy at Aguada, Puerto Rico, about 52 km to the west of the Arecibo Observatory. Although the NAU transmitter operates exclusively for Naval communications, its proximity to the Arecibo Observatory offers occasional opportunities to observe geophysical effects of whistler-wave interactions with radiation belts. Most of NAU's emitted power propagates in the Earth-ionosphere waveguides. However, in the presence of ionospheric plasma irregularities some fraction of the NAU carrier signal scatters into the ionosphere and magnetosphere where it propagates along magnetic field lines in the whistler mode. This report focuses on experiments in which the Arecibo Incoherent Scatter Radar and ionosonde monitored properties of local ionosphere on the night of January 1-2, 2006. Spread F events were monitored continuously by the ionosonde, and they occurred and lasted for several hours during our experiments. We examine possible correlations between occurrences of nighttime E-region plasma line (PL) enhancements over Arecibo and 40.75 kHz NAU emissions. On the night of January $1 - 2$, 2006, the experiments were conducted from 22:00 to 6:00 local time (LT). NAU transmitter was initially turned off until 01:45 LT, when continuous operations resumed for the remainder of the experiments. Enhanced PL events lasting < 10 s had central frequencies and bandwidths of about 2.5 and 1.5 MHz, respectively, indicating that Arecibo radar detected 2.3 to 8.5 eV suprathermal electrons streaming along geomagnetic fields. The rate of PL event detections increased by a factor of 2.8 after NAU turn-on. We suggest that 40.75 kHz radiation sporadically leaked though local ionosphere, probably abetted by field-aligned irregularities. The radiation propagated in whistler mode into the $L = 1.35$ inner radiation belt where gyroresonant interactions with trapped 390 keV electrons increased the precipitation rate.

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1. Introduction

We have been conducting VLF wave injection experiments at Arecibo Observatory, Puerto Rico in the past several years to investigate whistler wave interactions with inner radiation belts as well as ionospheric effects caused by precipitated energetic electrons. The whistler waves used in our experiments were launched from the 100 kW and 40.75 kHz transmitter code-named NAU, which is operated by the United States Navy at Aguada, Puerto Rico, about 52 km to the west of the Arecibo Observatory. Although the NAU transmitter operates exclusively for Naval communications, its proximity to the Arecibo Observatory offers occasional opportunities to observe geophysical effects of whistler-wave interactions with radiation belts. Most of NAU's emitted power propagates in the Earth-ionosphere waveguides. However, in the presence of ionospheric plasma irregularities some fraction of the NAU carrier signal scatters into the ionosphere and magnetosphere where it propagates along magnetic field lines in the whistler mode. Puerto Rico is located at ~30° N magnetic latitude where it is magnetically conjugate to Argentina through the inner radiation belt at L = 1.35.

1.1. Arecibo Experiments with An HF Heater

These VLF wave injection experiments were motivated by our ionospheric HF heating experiments performed in 1990's. We reported results of 1997 Arecibo experiments in which the HF ionospheric heater at Arecibo created large, sheet-like ionospheric density irregularities that aligned parallel to the magnetic meridional plane [Lee et al., 1998]. These induced irregularities extended to great heights above the heated volume and acted as "ionospheric ducts" or parallel-plate waveguides for whistler-mode wave propagation experiments. As part of the experiments identical VLF-receiver antennas were set up at Arecibo, Puerto Rico and the magnetic conjugate near Trelew, Argentina. The local receiver monitored detailed characteristics of the emitted carrier waves for comparison to those detected at Trelew. Starks and Lee [1999] and Starks et al. [2001] used different time delays to distinguish between signals confined to the Earth-ionosphere waveguide and those guided by "heater-induced ionospheric ducts" to propagate along the L = 1.35 magnetic field lines. Ducted NAU-generated 28.5 kHz whistler mode was recorded in Trelew, Argentina near the magnetic conjugate point of Arecibo [Starks et al. 2001]. Note that NAU now transmits at 40.75 kHz rather than 28.5 kHz for communications operation. The ray tracing work of Starks [2002] suggested that significant quantities of radiation from NAU did get into the magnetosphere.

When the NAU 28.5 kHz signals propagate upward in the whistler-mode from Arecibo to the conjugate location near Trelew, whistler wave-electron interactions in the radiation belts can cause trapped electrons to precipitate into the atmosphere. In our 1997 experiments, ducted and subionospheric signals from NAU were recorded by receivers deployed at Arecibo and Trelew during HF heating. The Arecibo data served as source image for processing the signals by matched filter technique [Starks and Lee, 2000], and thus allowed removal of the subionospheric component. Figure 1a shows the transit times of whistler-mode signals measured between 21:15 and 23:30 LT on July 24, 1997,

and Figure 1b shows the corresponding uncalibrated amplitudes. Note the presence of several long-delay events (greater than 0.7 s), detected mostly early in the period. These events most likely represent weak unducted whistler-mode emissions that were washed out by stronger ducted signals detected later in the experiment. This speculation is supported by propagation simulations performed using the IGRF geomagnetic field and PIM ionosphere/plasmasphere models. Those simulations demonstrate that on this particular evening 28.5 kHz whistler-mode signals could not duct beyond L=2.4, with a corresponding transit delay of about 0.45 s [Starks et al., 2001].

For the first 28 minutes (Period A), the HF heater operated in a 20 ms on/980 ms off pulsing sequence, injecting X-mode waves at 5.1 MHz. The heater was turned off at 21:43 for 11 minutes (Period B). Operation was resumed at 21:54, transmitting CW O-mode waves at 3.175 MHz for 31 minutes (Period C). From 22:25 until 23:13 (Period D) the heater was switched to the 20 ms on/980 off pulsed O-mode. At 23:13 the heater transmitted CW X-mode until the end of the detectable 28.5 kHz wave recording (Period E). We note that results similar to those shown in Figure 1 were also obtained on all three nights, for which we have reduced the data.

Figure 1a shows that between Periods A and C, the measured transit times of the NAU signals from Puerto Rico to Trelew decreased from largely unducted values near 1 s to about 0.16 s. The latter transit time is consistent with IGRF simulated values for ducting of whistler-mode emissions along the L=1.35 field line colocated with the Arecibo Observatory. Figure 1b shows that during the same interval the received detected intensities nearly doubled. This suggests that the operation of the HF heater in CW O-mode during Period C facilitated the conjugate propagation of NAU signals along the local L=1.35 field line. Signals coupled more effectively into preexisting local high-altitude ducts in the presence of HF-induced large sheet-like irregularities, resulting in higher signal strengths for ducted emissions. These stronger signals were detected preferentially by the data processing, suppressing detection of what are probably omni-present unducted emissions and ducted signals on a variety of L-shells. These local duct interfaces were apparently not well-maintained during Period D by the pulsed O-mode heating, causing the ducted signals to become comparable in strength to signals traveling on other unenhanced paths. By Period E, local ducting has ceased altogether and the unducted modes disappeared thereafter. Note that–the resolution of the data analysis tripled during Period E as the detected emissions began to disappear, accounting for the similar number of detected events in Period D.
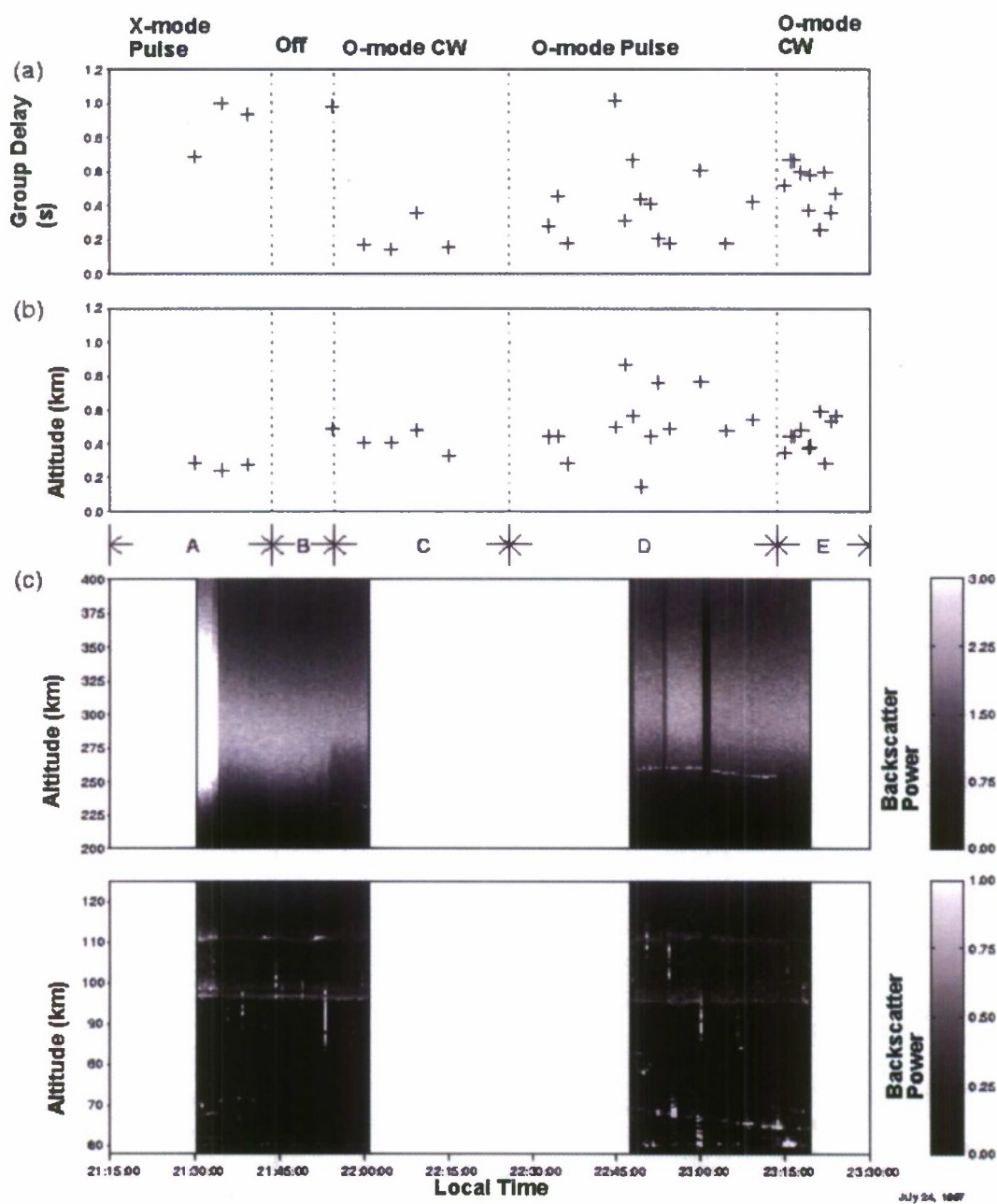
Figure 1. (a) Transit times and (b) intensities of the 28.5 kHz wave recorded at Trelew (Argentina), the geomagnetic conjugate point of Arecibo (Puerto Rico); (c) RTI plot of radar backscatter power showing ionospheric features in the F region and suspected events of whistler-triggered particle precipitation into the lower ionosphere over Arecibo.

Based on the present experiments, it is impossible to determine whether the 28.5 kHz

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whistler-mode signals propagated across the inner radiation belt to Trelew in the ducted or unducted modes. The observed 0.16 s delay time is consistent with propagation in a duct. However, VLF waves from ground-based transmitters have been observed by the ISEE-1 satellite in the inner magnetosphere propagating as unducted whistlers [Bell and Ngo, 1988]. Generally, unducted whistler signals propagate only to locations where their frequencies match the local lower hybrid resonance frequency. There they can reflect back into the magnetosphere [Kimura, 1966]. To exit the magnetosphere, low-frequency unducted whistler modes would require field-aligned plasma irregularities [Bell and Ngo, 1990]. Along the L=1.35 field line, 28.5 kHz is always greater than the lower hybrid resonance frequency, and signals could propagate as unducted whistler-modes to reach the ionosphere above Trelew. Thus, they should only experience one hop with a possible specular reflection at the ionosphere in the conjugate hemisphere.

Displayed in Figure 1c are range-time-intensity (RTI) plots of the Arecibo radar backscatter power measured from 21:30:19 to 23:19:32 LT. Between 22:00:48 and 22:47:33 LT, a data gap occurred. In this display a gray scale is used with bright and dark regions corresponding to strong and weak backscattered power, respectively. The top and bottom panels of Figure 1c show ionospheric features in the F-region near the reflection height of the HF heater and at lower altitudes, respectively. No measurable backscatter came from intervening altitudes. The reflection heights of the 3.175 MHz heater wave were about 230 and 255 km in Periods C and D, as indicated by bright lines. The night-time ionosphere usually contains few free electrons at D and E region altitudes. We note, however, that layered structures appeared episodically between 60 and 120 km. The two continuous bright lines near 100 and 110 km represent backscattered power from persistent sporadic E layers. Discrete bright vertical lines (e.g., around 21:38, 21:44, 21:48, 21:52, 22:55, 23:00) are signatures of meteor-produced ionization [Zhou and Mathews, 1994]. The most intriguing feature is the presence of brief, horizontal dashed lines, recorded in Periods A, D, and E, in the 60 - 80 km altitude range. Their shapes are different from the V or U-shaped lines characteristic of backscatter from ships or airplanes [Zhou and Mathews, 1994]. One such example appears near 22:50 LT. Although we could not rule out the possibility that they were caused directly by the heater waves, a plausible speculation is that the horizontal dashed lines came from thin ionization layers that were produced by energetic electrons, precipitated from the radiation belts by ducted 28.5 kHz whistlers and stopped in the atmosphere.

Arecibo is situated at the foot print of the L=1.35 magnetic flux tube, and just to the west of longitude sector containing the South Atlantic Anomaly. Eastward drifting quasi-trapped electrons undergo maximum precipitation in this longitude sector where the atmospheric loss cone is large [cf. Figure 1 of Luhmann and Vampola, 1977]. Precipitation would result from the pitch-angle scattering of marginally trapped electrons by 28.5 kHz whistler-mode signals, introduced into the radiation belt through naturally occurring or heater-enhanced ionospheric scattering. Electron precipitation from a continuous 28.5 kHz transmission is expected to be brief or episodic, due to relatively small inhomogeneities in the pitch angle distributions of energetic electrons that gradient-

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curvature drift across the Arecibo flux tube. Observations of such wave-particle interactions are not unprecedented. During experiments conducted with the S-81 satellite, Imhof et al [1983] observed the controlled precipitation of energetic electrons from the magnetosphere in response to modulated bursts of 17.8 kHz radiation from the NAA transmitter in Cutler, Maine. During other SEEP experiments precipitating electrons with E > 45 keV were detected in conjunction with VLF radiation bursts from the Siple station in Antarctica [Imhof et al, 1989] and lightning [Inan et al, 1989]. Measurements from the SAMPEX satellite, available at http : //cdaweb.gsfc.nasa.gov/cdaweb/istp_public/, indicate that the inner radiation belt contained significant fluxes of energetic electrons at the time of the Arecibo experiments.

1.2. Arecibo Experiments without HF Heater

As mentioned earlier, it is plausible that the NAU-launched 28.5 kHz whistler-mode waves can interact with ionospheric plasmas and precipitate energetic electrons from the radiation belts. The further study of these processes discontinued unfortunately, after the Arecibo HF heater was damaged by Hurricane Georges in 1998 and later dismantled. While the loss of the HF heater renders the controlled creation of ionospheric ducts for NAU whistler-mode wave injection experiments impossible, we began to look into the possibilities of conducting Arecibo experiments using naturally occurring large-scale ionospheric irregularities in the presence of the spread F process. It is reasonable to expect that NAU-generated whistler-mode waves also scatter off and are guided by natural irregularities to propagate into the ionosphere and magnetosphere along Earth's magnetic field [Labno et. al., 2007]

Over the past three years we conducted a series of experiments using the Arecibo 430 MHz incoherent scatter radar (ISR) to identify large plasma irregularities and monitor possible ionospheric plasma disturbances induced by NAU transmissions. Section 2 summarizes ISR detections of sporadic enhanced plasma-line backscatter from the E layer above Arecibo. When compared with NAU's OFF/ON history, the distribution of prominent E-layer events suggests that nearby transmitter was their probable cause. Section 3 develops a plausible scenario to explain how NAU-generated whistler-mode waves pitch-angle scatter electrons trapped in the inner radiation belt, causing them to precipitate into the lower ionosphere above Arecibo where sporadically enhanced plasma-line effects were detected by the ISR.

2. Arecibo Experiments

This report focuses on experiments in which the ISR and an ionosonde monitored properties of local ionosphere on the night of January 1-2, 2006 [Pradipta et al., 2007]. Spread F events were monitored continuously by the ionosonde, and they occurred and lasted for several hours during our experiments. Nighttime experiments avoid photoelectron contamination from the local and conjugate hemispheres. The 430-MHz radar emits in a highly focused, 1.6° wide beam and operates in two modes that we refer

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to as backscatter-power (BP) and plasma-line (PL) measurements. Throughout experiments reported here the radar transmitted vertically from a stationary linefeed. During BP operations the receiver was tuned to 430 MHz to determine height profiles of plasma densities from the time histories and intensities of reflected signals. PL operations used a coded-long pulse technique to sample altitudes between 90 and 495 km with a height resolution of 150 m. Here the receiver observed the time history of reflected waves at frequencies within the 430 ± 7 MHz band. Altered frequencies result from the Doppler-shifting of signals that have coherently scattered off plasma modes with wavelengths near 0.35 m, propagating toward/away from the radar. At ionospheric altitudes the plasma modes are excited by electron beams that match the phase speed of the waves.

We also fielded a VLF/LF receiver to monitor the status of NAU operations. The NAU transmitter was turned off when ISR experiments began at 22:00 local time (LT) on January 1. It remained off until 01:45 on January 2 when operations resumed and continued uninterrupted through 06:00 when our observation period ended. During the entire 8 hour period the ISR looked to local zenith, operating in repeated sequences of 20-minutes BP and 10 minutes PL operations.

The geometry of the experiments is schematically illustrated in Figure 2. Signals transmitted from NAU mostly propagate at subionospheric altitudes (Ray 1) within the Earth-ionosphere waveguide. In addition, when 40.75 kHz waves reach the interface between the neutral atmosphere and the ionosphere, some fraction of the transmitted power penetrates the ionosphere (Ray 2) via refraction and mode conversion. Using a simplified slab model of ionospheric plasmas, we can compute the transmission coefficient and, subsequently, estimate that ~15% of the incident NAU power can couple into the ionosphere at the altitude of the nighttime F region. As indicated in our earlier experiments [Labno et al., 2007], coupling between NAU transmissions and the ionosphere was enhanced when spread F irregularities were present, while E region irregularities were absent in our nighttime experiments. Gradients at the edges of large field-aligned irregularities can act as waveguides that direct linearly polarized NAU signals along the Earth's magnetic field. Following the physics (optics) convention, the left (right)-hand circularly polarized component of guided NAU signals converts into a whistler mode. Therefore, the overall coupled power in whistler-mode wave is ~7.5 % of the incident NAU power.
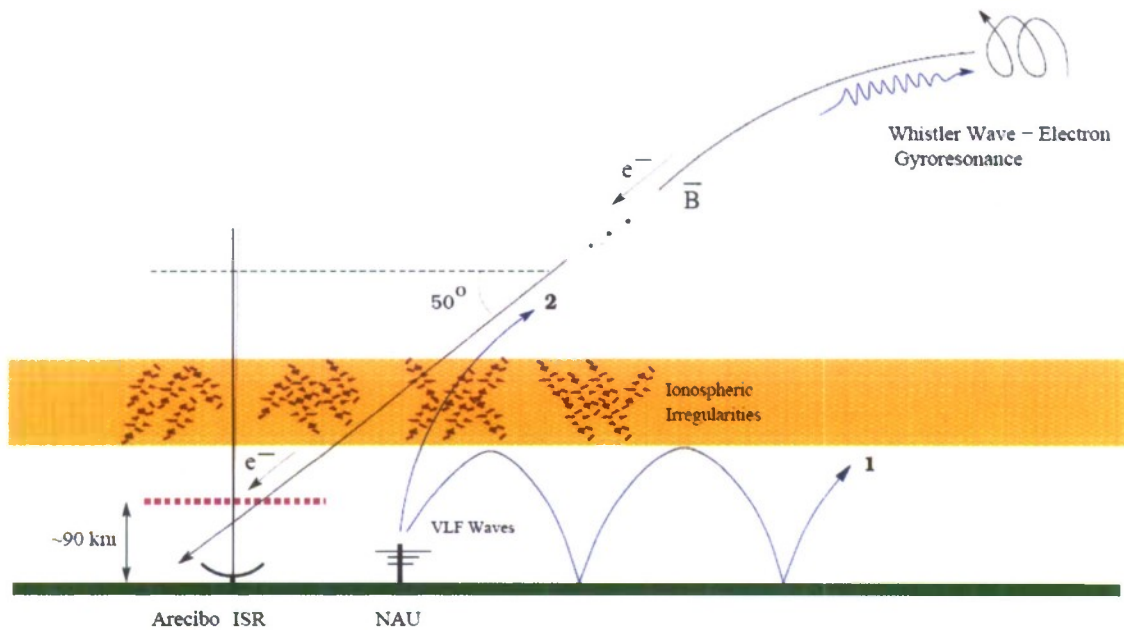
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Figure 2. Geometry and scenario of Arecibo experiments. Signals at 40.75 kHz emitted from NAU can propagate either as subionospheric waves (denoted by Ray 1) or whistler-mode waves along the Earth's magnetic field in the ionosphere (denoted by Ray 2). The coupling of NAU signals into the ionosphere is enhanced by ionospheric irregularities. Whistler-mode waves can then interact with energetic electrons in radiation belts at L = 1.35, and subsequently cause electron precipitation into the lower ionosphere over Arecibo.

Figure 3 shows a typical set of PL measurements in the form of three frequency-altitude-intensity (FAI) spectra. From left to right the FAI plots indicate results of PL sequences that began at 05:01:07, 05:01:17, and 05:01:27 LT on January 2, 2006. The middle plot shows an E-layer PL enhancement characterized by spiky bursts that last for a short period of time. The intensities of PL signals are marked by vertical lines with lengths linearly proportional to backscattered power, given in arbitrary units. Each PL spectrum was acquired over a 10 s integration time. The enhanced PL events have a signal-to-noise ratio (SNR) of 4 to 5 and appeared at altitudes near 120 ± 20 km. Near this time neither the ISR backscatter power profile nor the ionograms showed the presence of significant E-layer or sporadic E plasmas. The enhanced plasma line spectrum has center frequency of ~2.5 MHz with a ~1.5 MHz bandwidth. Figure 3 also shows no PL enhancements in samples acquired before or after the event recorded between 05:01:07 and 05:01:17 LT. These data suggest that E-layer PL enhancements above Arecibo are episodic phenomena of < 10 s duration.
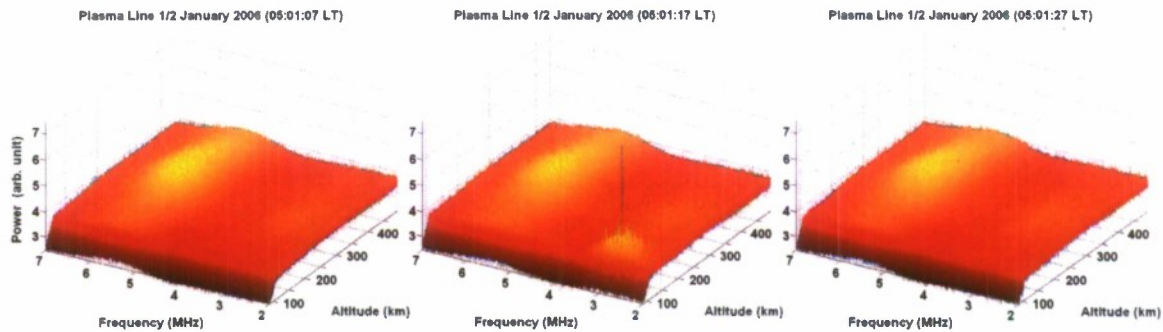
Figure 3. A set of typical E-region plasma line enhancement data (FAI plots) recorded when NAU transmitter was turned on. The middle plot shows the presence of spiky, brief (< 10 s) plasma line enhancement with a SNR of 4-5 at altitudes of 120 ± 20 km. The enhanced plasma lines have a center frequency of 2.5 MHz with a bandwidth of 1.5 MHz.

Figure 4 shows the timeline for ISR experiments conducted on the night of January 1 – 2, 2006. Heavy red dashed lines mark PL mode operations. NAU ON/OFF periods are indicated below the local-time axis. Fourteen PL mode operations (840 ten-second samples) occurred with/without NAU transmissions. We assigned PL enhancement levels as relative powers according to SNR, quantized as multiples of 0.5. For example, cases with SNR = 4 and 2 have power levels of 1and 0.5, respectively. The bar chart display in Figure 4 clearly shows that the occurrence rate of PL enhancements at E-layer altitudes increased significantly after NAU turned on at 01:45 LT.
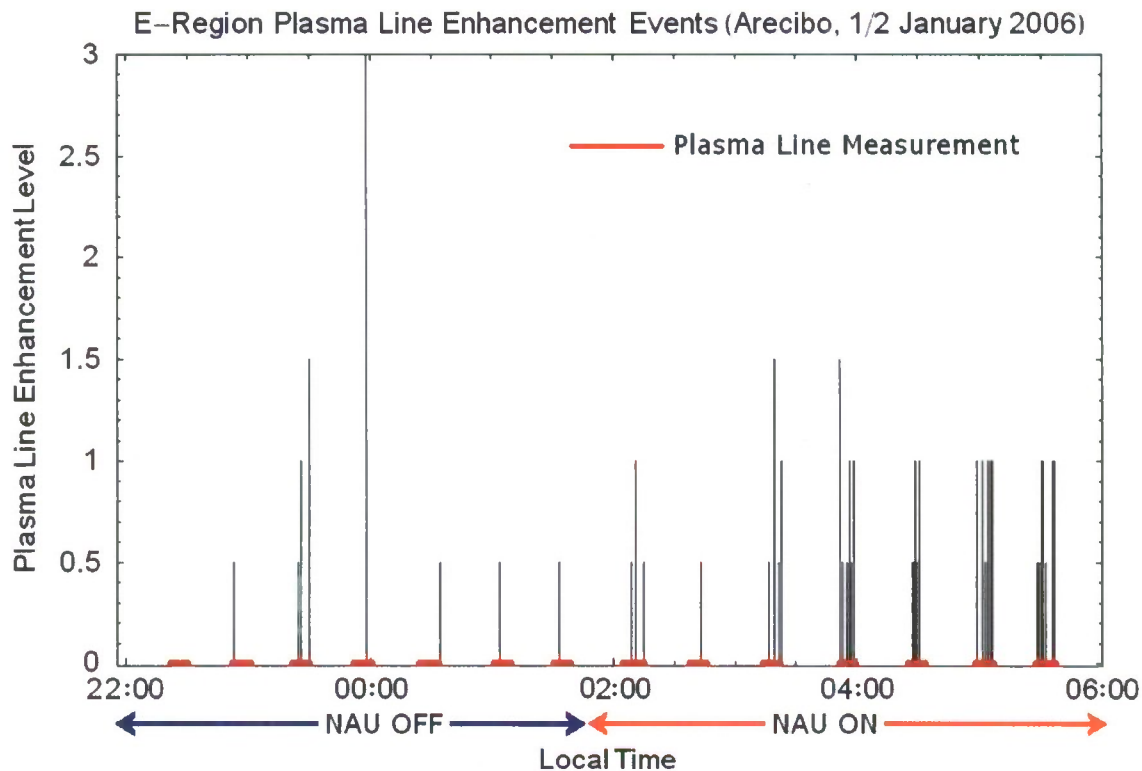
Figure 4. The occurrence rate of E-region plasma line enhancement increased rapidly after the NAU transmitter was turned on, demonstrating that NAU-generated 40.75 kHz whistler-mode waves can cause prominent E region plasma effects [Pradipta et al., 2007].

The average occurrence rate increased from 0.25 event per minute when NAU was OFF to 0.75 event per minute when NAU was ON. The plot of E Region PL Enhancement Event Rate on the night of 1/2 January 2006 is given in Figure 5. We recorded 16 (1.9%) PL enhancement events while NAU signals were absent and 45 (5.35%) after transmissions resumed. This factor of 2.8 increase in PL enhancement rates between NAU ON/OFF periods strongly suggests that a causative relationship between them. If events with intensity below 0.5 are excluded, there are 5 events with NAU OFF and 18 events with NAU ON, showing even more contrasting effects of NAU ON-OFF operation with a factor of 3.6 increase in PL enhancement rates [Pradipta et al., 2008].

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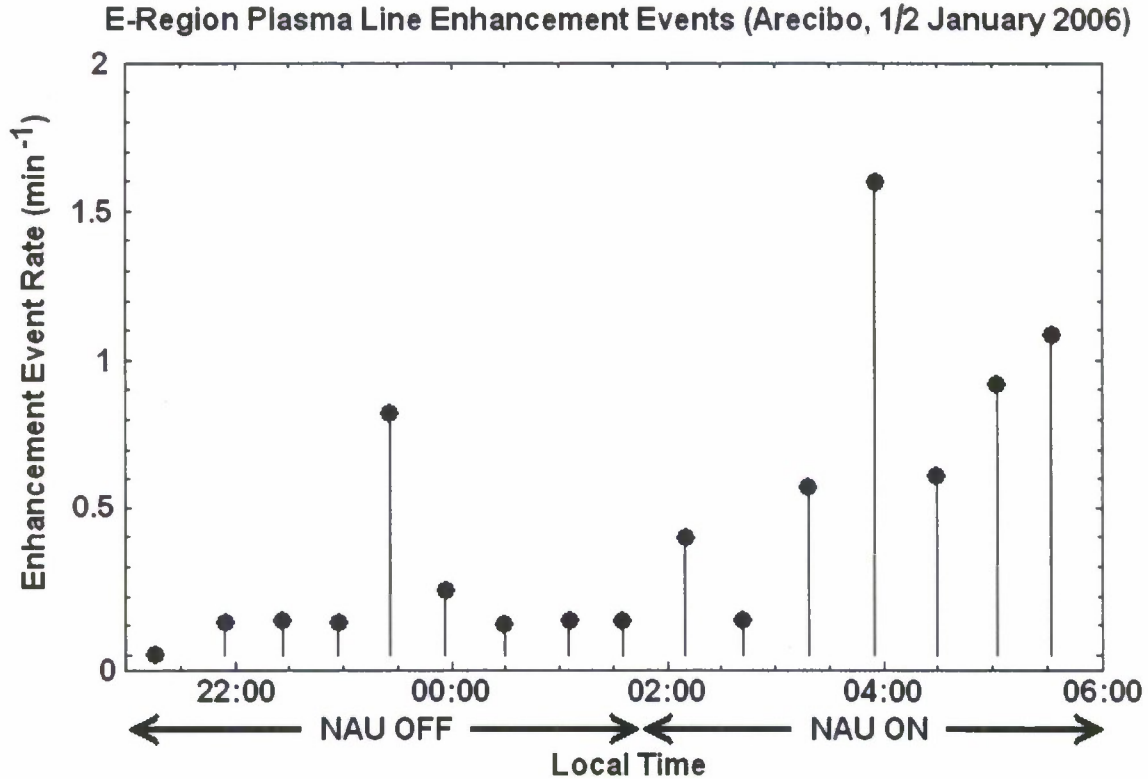E-Region Plasma Line Enhancement Events (Arecibo, 1/2 January 2006)

Figure 5. The plot of E Region PL Enhancement Event Rate (i.e., no. of events per minute in each of the 10 minute PL measurement period) on the night of 1/2 January 2006. This is an alternative way to display our 1/2 Jan 2006 PL data, showing that, on the average, the event rate had tripled when NAU was ON in comparison to that when NAU was OFF.

3. Discussion

Although PL enhancements in the E layer often appeared in Arecibo measurements, prior to January 1 - 2, 2006 experiments, it was impossible to demonstrate an unambiguous correlation between their occurrence and NAU transmissions. As an operational Navy communications device, NAU activity is beyond our control. By happenstance on the night of January 1 our VLF/LF receiver detected no NAU signals from 22:00 to 01:45 on January 2, indicating that the transmitter was turned off. From 01:45 through the end of our experiments at 06:00 our VLF/LF receiver showed that the NAU transmitter had returned to continuous operations. This unexpected sequence provided an opportunity to test for correlations between PL enhancements and 40.75 kHz emissions.

Returning to Figure 2, the schematic shows some Ray 2 signals from NAU scattering off spread F irregularities along field-aligned ionospheric ducts into the magnetosphere. In the magnetosphere Ray 2 signals propagate in either the ducted or unducted whistler-mode. Ducted whistler signals can reach the conjugate locations near Trelew, Argentina

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in the southern hemisphere. Unducted whistler waves reflect back toward the equatorial plane of the magnetosphere at altitudes where their frequencies match that of the local lower-hybrid resonance [Kimura, 1966]. However, for 40.75 kHz whistler-mode waves, there is no LHR surface available to magnetospherically reflect the unducted waves. Thus, they will only experience one hop with possible specular reflection at the ionosphere in the conjugate hemisphere. Energetic electrons that see these waves Doppler shifted to their local gyrofrequency scatter in pitch angle. If the scattering is sufficiently strong some electrons trapped in the inner radiation belts precipitate into the atmosphere to create new free electrons. Field–aligned beams of secondary electrons and radiation-belt primaries with residual energies < impact ionization energies ~13 eV [e.g., Brown, 1967] were detected by Arecibo radar.

The PL frequency distribution centered at ~2.5 MHz with a bandwidth (Doppler spreading) of ~1.5 MHz indicate that the phase speeds of streaming suprathermal electron-induced waves off which the radar scattered were in the range 6.2×10^5 to 1.2×10^6 m/s. The corresponding energies of resonant streaming electrons fall in the range 2.3 – 8.5 eV [Carlson et al., 1982]. The unperturbed densities and temperatures of plasma in the nighttime E layer at mid latitudes are very low, and support no electrons in this energy range. We conclude that the ISR detected effects of suprathermal electrons, introduced by an external agent. In the E layer the mean free path (a few kilometers) of electrons with energies of a few eV is small. Thus, they had to be created locally. The magnetic conjugacy of NAU through the inner radiation belt leads us to look there for the source.

The equatorial region $1.2 < L < 2.5$ constitutes the domain of the inner radiation belt in which energetic electrons and ions are magnetically trapped and follow gradient-curvature-drift orbits around the Earth. Measurements taken near the equatorial plane during the Combined Release Radiation Effects Satellite (CRRES) mission show that the spectrum of trapped electrons is described by an exponential relation $j(E) = j_0 \exp [-(E/E_0)]$, where $E_0 = 0.18$ MeV and $j_0 \approx 4 \bullet 10^7$ $(cm^2 \ s \ sr \ MeV)^{-1}$ [D. H. Brautigam, personal communication, March 2004]. The inner radiation belt is collocated with the inner portions of the geo-corona and plasmasphere, respectively, that are populated with gravitationally bound neutrals and cold plasma of ionospheric origin. The region is also characterized by broadband low-frequency electromagnetic waves that propagate in the unducted whistler mode. Trapped electrons escape magnetic confinement via either gyroresonant wave-particle interactions or Coulomb collisions with the nuclei of geo-coronal neutrals and/or plasmaspheric ions.

Kennel and Petschek [1966] showed that whistler-mode radiation pitch-angle scatter energetic electrons that meet the gyro-resonance condition

$$\omega_0 + k_\parallel \ v_\parallel = \omega_{ce} \ [1 - (v_\parallel^2 + v_\perp^2)/ \ c^2 \ ]^{\frac{1}{2}} , \qquad\qquad (1)$$

$k_{\parallel}$ is determined from the whistler wave dispersion relation:

$$(ck_o/\omega_o)^2 \approx \omega_{pe}^2/(\omega_o\,\omega_{ce}) \qquad\qquad\qquad (2)$$

where ω_o and $(k_{\parallel})$ k_o denote, respectively, the frequency and (parallel) wave number of the 40.75 kHz whistler-mode wave; ω_{ce} and ω_{pe} represent the angular cyclotron and plasma frequencies of cold plasmaspheric electrons. The symbols $v_{\parallel}$ and $v\bot$ represent the velocity components field of collocated radiation belt electrons parallel and perpendicular to the magnetic field; c is the speed of light in a vacuum. Note that the calculation of this electron energy employs a relativistic correction to the gyro-resonance condition given by Kennel and Petschek [1966].

For simplicity we assume that NAU-generated whistler-mode waves propagate along Earth's magnetic field, i.e., $k_{\parallel} = k_o$. We also approximate the equatorial plasma frequency $(\omega_{pe}/2\pi) = 0.57$ MHz (corresponding to a plasmaspheric electron density of 4,000 cm^{-3}), the electron cyclotron frequency $(\omega_{ce}/2\pi) = 0.32$ MHz. At the magnetic longitude of interest the loss cone angle is 33° wide over Arecibo. Combining equations (1) and (2) we calculate that 40.75 kHz whistler-mode waves interact resonantly with electrons with energies near 390 keV. CRRES spectral measurements cited above indicate that the inner radiation belt contains an ample supply of electrons at this energy.

Arecibo is situated at the foot of the L = 1.35 magnetic flux tube, near the westward edge of the South Atlantic Anomaly (SAA). Eastward drifting, inner-belt electrons undergo maximum precipitation in this longitude sector at the southern end of flux tubes where the magnetic field is weak and consequently the atmospheric loss cone is large [Luhmann and Vampola, 1977]. The angular widths of the equatorial loss cone for electrons reaching the ionosphere above Trelew and Arecibo are 47° and 33°, respectively. The loss cone is ~14° wider in the southern than the northern hemisphere. This magnetic asymmetry renders electron precipitation far more likely to occur in the southern than northern hemisphere. This is demonstrated daily in the contamination of sensors on DMSP satellites by energetic particles above Trelew but not Arecibo.

The large difference between the widths of the loss cone makes it seem unlikely that NAU-generated whistler-mode waves would scatter many energetic electrons by 14°. In fact the sporadic PL enhancements reported above confirm this conjecture. Pitch-angle scattering is a diffusion process based on wave-particle interactions that are essentially stochastic. NAU generated whistler-mode waves, whether ducted or unducted, should pitch-angle scatter energetic electrons in the inner radiation belt, but very few by 14° or more. After mirroring in the northern hemisphere most pitch-angle scattered electrons should precipitate at the southern end of the field line. The very few electrons scattered by 14° mirror to E-layer altitudes where they would collide with ambient neutrals to create new ion-electron pairs. Newly created secondary electrons would then move upward and downward along the magnetic field away from the collision sites. As the secondary electrons and precipitated primaries with residual energies streamed along the

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Earth's magnetic field, ISR waves coherently backscattered from them. The Doppler-shifted backscattered waves were consequently detected as PL enhancements.

During the On-Off operation of NAU transmitter on January 1-2, 2006, a total of 16 natural electron precipitation events were recorded, when NAU transmitter was off from 22:00 to 01:45 LT the next day (Figure 3). Since no thunderstorm activity occurred nearby, we attribute these 16 electron precipitation events to Coulomb scattering encounters with geo-coronal neutrals or plasmaspheric ions. Induced precipitation events resulted from the stochastic pitch-angle scattering of marginally trapped electrons by 40.75 kHz whistler-mode waves that entered the inner radiation belt through naturally occurring ionospheric ducts. This expectation is indeed consistent with the increased rate of 45 PL enhancement events observed after the NAU transmitter was turned on.

Finally, we should mention that we have found evidence from our August and December 2008 experiments that NAU whistler waves can "directly' accelerate ionospheric electrons via a mechanism distinctively different from that we reported in Labno et al., [2007]. In brief, we may be able to investigate some whistler wave-electron interaction processes, which occur in radiation belts, in our ground-based ionospheric experiments at Arecibo

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